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Waste energy recovery in seawater reverse osmosis desalination plants. Part 2: Case study

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ABSTRACT

The present study is a continuation of a previou[illegible]k which dea[illegible]e performance evaluation of seawater reverse osmosis SWRO plants equi[illegible] w[illegible]nergy recove[illegible]evices (ERDs). Energy recovery devices are an important part of any seawater [illegible]everse [illegible]sis system, and any future decrease in specific energy consumption is dependent upon the future deve[illegible]ent and improvement of such devices. The present study is applied on the 25[illegible]awater reverse [illegible]osis (SWRO) desalination plant that is currently under operation in Egypt[illegible] propylene & polypropylene (EPP) Company located in Port Said city, Egypt. The EPP seawater RO plant [illegible]sists of five m[illegible]r systems: seawater supply, seawater pretreatment, high pressure pumping with ene[illegible] recovery de[illegible]s, RO modules, and permeate post treatment. The plant is made up of two stages of [illegible]embrane [illegible]tems. The first stage consists of three similar trains of 94 m^3/h capacity ea[illegible]h and the fou[illegible]24 m^3/h capacity. The output water salinity from the first stage is 238 ppm [illegible]d as total [illegible]ved solids (TDS). Then the output flow from the first stage is treated again in the [illegible]ond [illegible]O units (three trains of 84 m^3/h capacity each) to achieve salinity of 8 ppm.

The objective is to pr[illegible]id results of the EPP-SWRO plant operation in order to measure and evaluate [illegible]formanc[illegible]provement due to using two different types of energy recovery devices (ERDs[illegible]

T[illegible]esults s[illegible]wed that, [illegible] the first pass, the effect of using ERDs leads to reduction in the SPC for all tra[illegible]hich[illegible] 6 and 7 down to 3:4 kWh/m^3. The resultant energy saving is 41:42%. While [illegible]e S[illegible]und to be [illegible].6:1.7 kWh/m^3 for the second pass. On the other hand, the actual recovery is between [illegible]d 34%, and 91 and 93% for the first and second passes respectively. Finally, an acceptable agreement [illegible]een actual and design results has been noticed.

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Nomenclature

BWRO brackish water reverse osmosis
DCS distributed control system
dP pressure drop, bar
EPP Egyptian propylene & polypropylene company
EPP-SWRO Egyptian propylene & polypropylene – seawater reverse osmosis plant
ERDs energy recovery devices
HPP high pressure pump
LP low pressure
NPSH net positive suction head
PX pressure exchanger
R membrane recovery, %
SI salinity increase
SPC specific consumption of electric power, [illegible]/m^3
SWRO seawater reverse osmosis
SWRO-ERDs seawater reverse osmosis coupled with energy recovery devices
TURBO turbocharger
VFD variable frequency drive

Subscripts
F feed
HP high pressure
P permeate
T turbine

Greek Symbols
η efficiency

1. Introduction

1.1. Reverse osmosis process

Following are some definitions that will help in understanding what a reverse osmosis process is and how it works with the aid of Fig. 1a and b [1]:

- Osmosis process is the tendency of water to flow through a semi-permeable membrane into a more concentrated solution as shown in Fig. 1a.
- Reverse Osmosis process is the passage of water out of a solution when a pressure greater than the osmotic pressure is applied on the solution side of a semi-permeable membrane, Fig. 1b.
- Semi-permeable Membrane: A membrane that allows water to pass through but rejects ions and molecules.
- Osmotic Pressure: The pressure needed to stop the flow of water through a semi-permeable membrane.
- Reverse Osmosis Membrane (RO): RO membranes act as a barrier to all dissolved salts and inorganic molecules, and molecules with a molecular weight greater than approximately 100. Rejection of dissolved salts is typically 95–99%. Trans-membrane pressures for RO typically range from 200 to 800 psi for seawater.

A large amount of energy is expended to achieve the required pressure levels for the process, which is then rendered useless after the process ends. By this, it is implied that the energy used to raise the pressure of the seawater feed goes to waste when the remaining brine, which is also at high-pressure, has to be eliminated as a waste.

A way had to be sought that would enable the reuse of the pressurized brine and would thus help in reuse of energy. The disposal of highly pressurized brine proved to be a major drawback of the

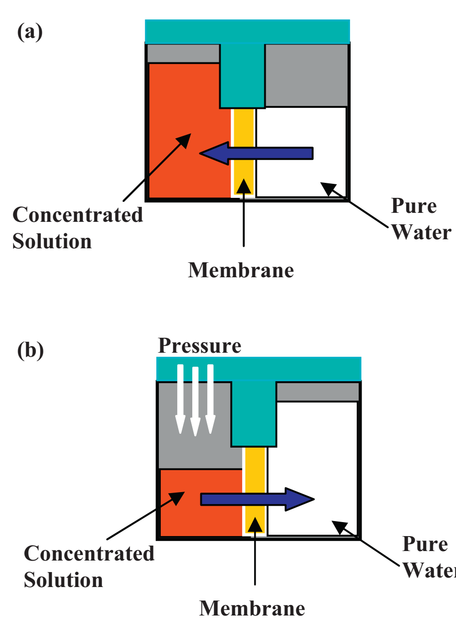


Fig. 1. (a) Osmosis process conceptual illustration [1]. (b) Reverse osmosis conceptual illustration [1].

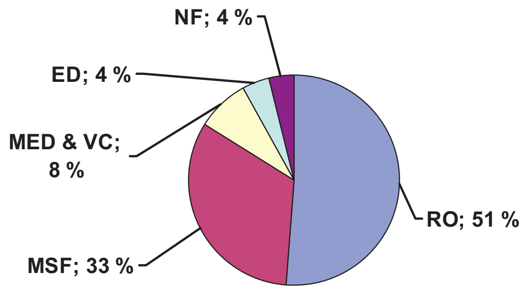


Fig. 2. Global installed desalting capacity by process (IDA Desalination Yearbook, 2007) [2,3].

system and led to an urgent need for the formulation of an efficient “energy recovery” process.

1.2. Why SWRO plants

Water desalination by the technique of reverse osmosis has proved to be the lowest energy consuming technique according to many studies. It consumes nearly around half of the energy needed for thermal processes [5–7]. Also, the modularity of reverse osmosis units, their simplicity of operation, their compact sizes and lower environmental impacts give them priority to be used for water desalination in remote areas. Water desalination by reverse osmosis units removes not only inorganic ions but also organic matters, viruses and bacteria. Reverse osmosis is widely used around the world; indeed, reverse osmosis processes accounted for 59% of contracted desalination capacity as of September 2008, having grown at a rate of 17% per year since 1990 [2].The globally instal[illegible] desalting capacity by process in 2007 is shown in Fig. 2.

Seawater desalination is being applied at 58% of installed capa[illegible]ity worldwide, followed by brackish water desalination accountin[illegible] for 23% of installed capacity [4–6].

1.3. Why energy recovery devices (ERDs) are use[illegible] SWRO [illegible]nts

Energy recovery devices (ERDs) are e[illegible]yed [illegible]rly all seawater reverse osmosis plants. The hi[illegible]operating [illegible]ures and low recovery rates produce conce[illegible]eject strea[illegible]ntaining significant quantities of ener[illegible] Ene[illegible]osts are one of the more significant costs in the [illegible]cycle cost [illegible]plant, accounting for up to 45% of lifecycle c[illegible][4–6]. Therefore[illegible] economically infeasible to operate SW[illegible]ants w[illegible]out energy recovery devices. Conversely, brackish w[illegible]reve[illegible]osmosis (BWRO) systems have low operating pressures [illegible] recov[illegible]rates. As a result, the concentrate stre[illegible]m th[illegible]syste[illegible]contain significantly less energy availa[illegible]or [illegible]overy. [illegible] these factors, many BWRO plants do [illegible]mploy[illegible]ergy recov[illegible]y technologies.

1.4. SWRO-(E[illegible]ypes

The ERDs are ma[illegible]s designed to recover the hydraulic energy of the concentrate stream. The process to recover the energy will vary depending on the type of ERD technology utilized. This paper will explain the most widely used ERD technologies in the market today: centrifugal Pelton wheel, Fig. 3b, centrifugal turbocharger, Fig. 3c, and isobaric pressure exchangers (PX) devices, Fig. 3d. ERDs operate under the same objective of reducing the high pressure pump (HPP) energy requirement. The following section will discuss and compare between the different three types of ERDs technology. However, every technology has some advantages and disadvantages, which are summarized in Table 1 and the detailed conclusive comparison is given in Appendix B. The following sections will discuss and compare between the different three types of ERDs [4–6].

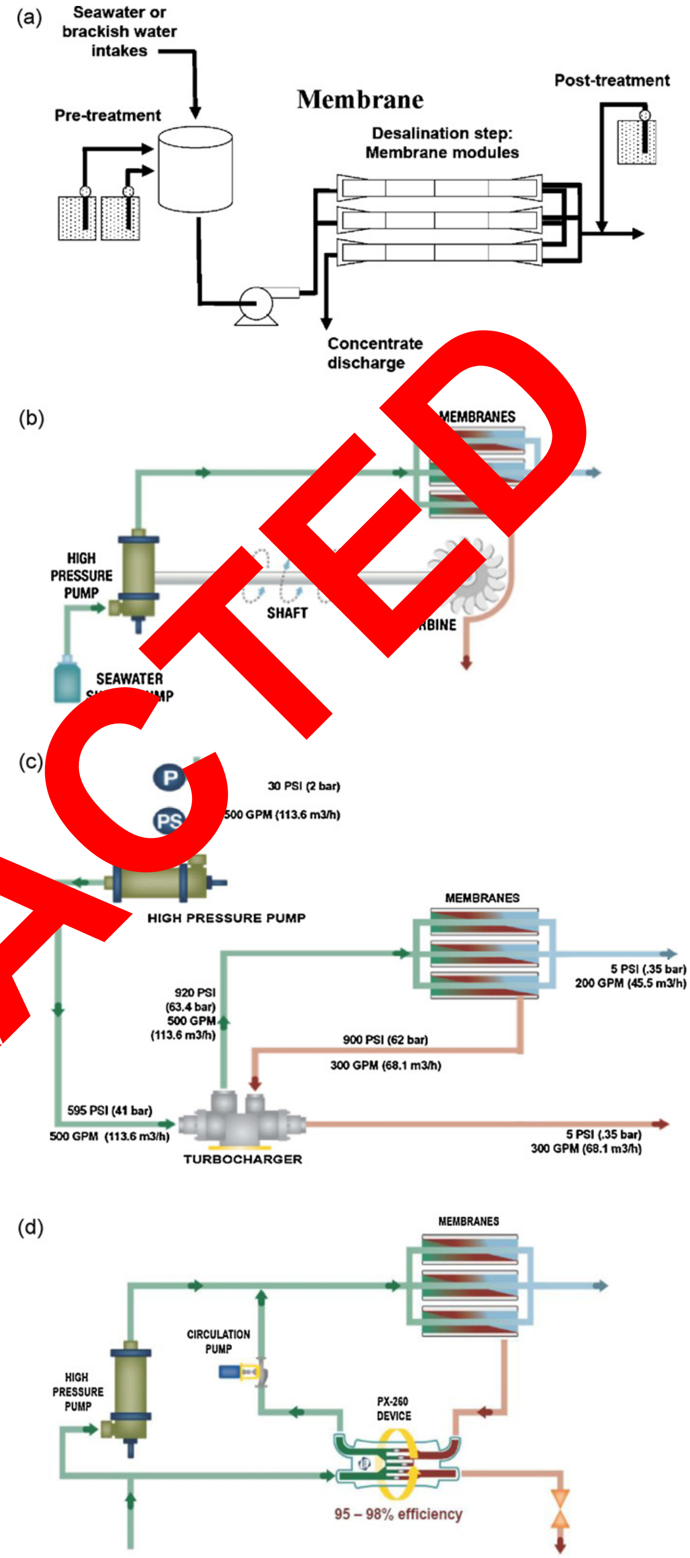


Fig. 3. (a) RO desalination unit without energy recovery [5]. (b) Pelton-wheel energy recovery [4]. (c) Turbocharger energy recovery [4]. (d) Pressure exchanger (PX) energy recovery [4].

1.4.1. SWRO with a turbine energy recovery devices

The SWRO desalination systems that use a turbine device as ERD is shown in Fig. 3b and its simplified layout is shown in Fig. 4.

The membrane concentrate is ejected at high velocity through one or more nozzles onto a turbine wheel. The turbine, coupled

Table 1
Comparison between the different three types of ERDs [5].

Description	Isobaric PX devices	Centrifugal turbocharger	Centrifugal Pelton wheel
Efficiency, %	98	81	78
Efficiency curve	Flat	Curved	Curved
Mixing, %	2–3	0	0
HP pump size	Sized for partial membrane feed flow, full membrane feed pressure	Sized for partial membrane feed pressure, full membrane feed flow	Sized for partial membrane feed pressure, full membrane feed flow
Footprint requirement	Relatively small compared to overall SWRO equipment	Relatively small compared to overall SWRO equipment	Relatively small compared to overall SWRO equipment
Periodic maintenance	No	No	Yes
Modularity	Yes	No	No

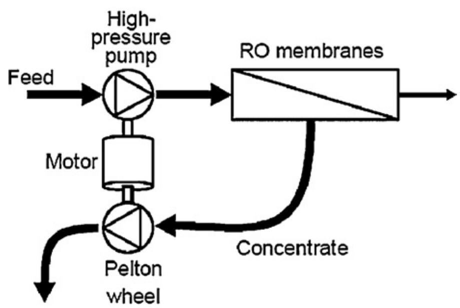


Fig. 4. Simplified layout for Pelton wheel ERDs [5].

to the high-pressure pump shaft, assists the motor in driving the pump that pressurizes the RO system. Energy is lost in a turbine ERD because it is transformed twice, once by the turbine and once by the pump impeller.

The water-to-water transfer efficiency of a turbine ERD sy... the product of the turbine and impeller efficiencies. The comp...nt efficiencies range from 70% to a maximum of 90%. Therefore ...e overall efficiency of a turbine ERD, is typically 50–75% [5–7].

1.4.2. SWRO with turbocharger energy recove... devices

The different inputs and outputs stre... of ...r (TURBO) are shown in Figs. 3c and 5)... hi...ssure typ... is designed to produce a pressure boo... RO feed s...ms using the hydraulic energy in the brine str... shown in ...5, the supply pressure feed passes throu... the ... pressure pump which provides a pressure boost ...hen the fee...ater passes through the TURBO, which provi... an additional ...t. The feed water then enters the memb...e pres...re vessels. A percentage of the feed water exits the ...mbra...s permeate. The rest exits as high pressure brine (concen...he brin...sses through the TURBO which extract...ressu...ergy ...e brine leaves the TURBO at low pressu... ...sal [5...

1.4.3. Iso...c e... devices

In addit... Fig. 3d, a simplified flow diagram of an SWRO process with i...ric ERDs is shown in Fig. 6.

The isobaric ERD, along with the ...ump, supplies a volume of pressurized feed water e...ntially eq...to the concentrate flow rate. The circulation pu...akes up fo...e membrane differential pressure, piping l...ses a... small d...erential pressure in the isobaric ERD. T...igh press...feed ...mp flow rate is reduced to that of the p...eate f...w. A r... the momentary direct contact betwe...e co...ntrate and feed water streams is a small amount ...f m...is mix...causes a small salinity increase at the ...mbrane ...d (ty...ly <3%) which results in slightly high...d pressure.

The iso...c E... not a centr...gal device and thus cannot create or "boost" press... The pressure of the feed water leaving the devi...qual to the ...ssure of the concentrate inlet pressure m...s the ERD (typically ...bout 10 psi). This pressure is completely i...ependent of the feed water inlet pressure. An energy recov... efficiency ...8% can be achieved with state-of-the-art isobaric E... A contro...lve after the ERD can be used to control the flow thr... the ...n pressure circuit.

The ...ive-displacement pressure transfer mechanism used ...sobaric ERDs deliver high efficiency despite pressure and ...ow rate variations. As a result, most SWRO plants being designed and built today utilize isobaric ERDs. Many plants built with centrifugal ERDs have been retrofitted or their operators are considering converting to isobaric devices to reduce energy consumption and increase production capacity. The largest SWRO trains operating today, 6.6 million gal/day such as in Hamma, Algeria, are supplied with PX Pressure Exchanger devices [5].

The late 1980s saw the emergence of a new technology that functioned on the "theory of work exchange". It involved a direct transfer of hydraulic energy of brine to hydraulic energy of feed, lacking the "drag" that would have resulted from the passage of the water through the shaft. This brought the technology closer to 90% efficiency [5]. Finally the ERDs development history is illustrated in Fig. 7 and different configurations of SWRO-ERDs are given in Appendix A, for more details.

1.5. Why two pass SWRO configurations

Many SWRO plants like the one under study, are designed and built with a very strict requirements on final product quality usually a very low concentrations of TDS is required for special applications such as water tube boiler plants. Such requirements are achieved

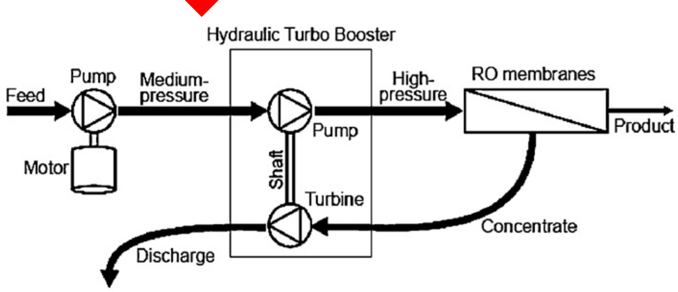


Fig. 5. Simplified layout for turbocharger ERDs [5].

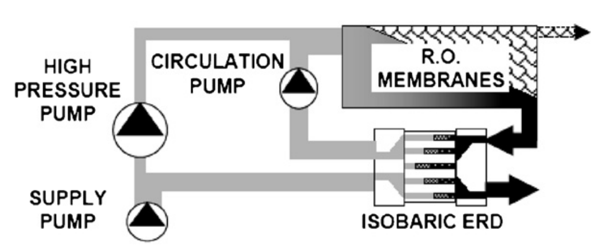


Fig. 6. Simplified diagram of an SWRO process with isobaric ERDs [5].

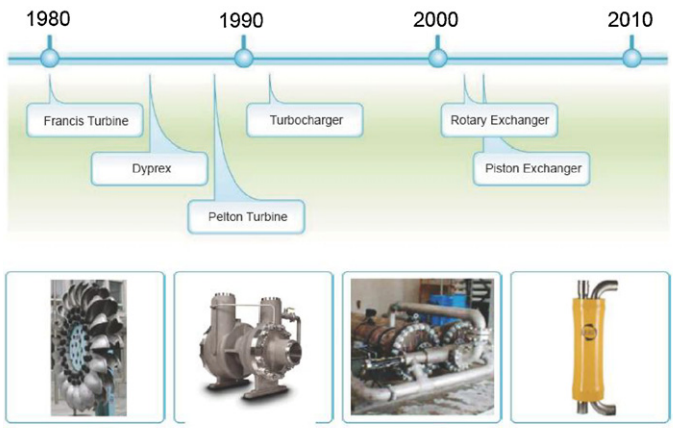


Fig. 7. ERD development history [4].

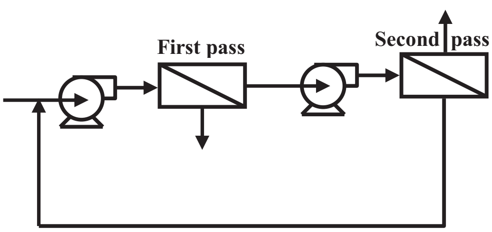


Fig. 8. Full second pass flow diagram [8].

with full two pass RO configuration. For understanding the SWRO under study, some definitions of two pass SWRO configurations given below [8].

1.5.1. Two pass RO design options

There are two main design option of two pa... ...ystem, depending on the final product quality requireme...

1.5.1.1. Full second pass. 100% of permeate flow ... is treated by second pass RO to obtain ...uired ...uct quality and quantity. Typical recovery of tw...ass SWRO ...em: First pass–50%, Second pass–90%, Total ...ith second ... brine recycle as shown in Fig. 8.

1.5.1.2. Partial second pass ...rtion of the first ... RO permeate is treated by second pas... and ...eate from both RO passes is blended together to ach... fi... product of required quality and quantity. Typical recovery ...tial tw...ss SWRO system: First pass–50%, Seco... 90%, ...l–4...% with second pass brine recycle as sh... in F... 9. Parti... ...nd pass system has the following ma... ...dvanta... against fu... second pass design:

- Smaller seco... ...ss RO trains.
- Higher total sy... recovery.

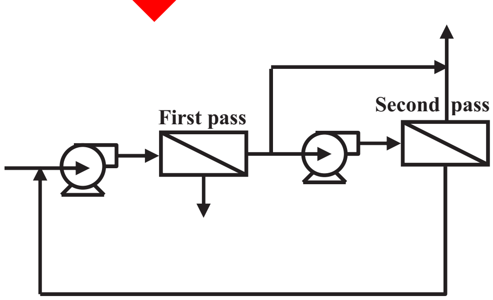


Fig. 9. Partial second pass flow diagram [8].

- Reduced capital cost (number of pressure vessels and membranes, smaller foot print, less high pressure piping and fittings)
- Reduced operating cost (lower energy and chemical consumption, less maintenance, smaller quantity of spare parts, reduced replacement and storage cost of RO membranes.

The present study gives an outline description of a reverse osmosis seawater plant (SWRO). The considered plant has been constructed on the site of Egyptian propylene & polypropylene (EPP) Company in Port Said city, Egypt. The plant is equipped with a distributed control system (DCS) using the-state-of-the-art computerized technology.

The saline water is supplied from 7... ...on the beach of the Mediterranean Sea. The salinit... feed sea...er is in the order of 43,110 ppm. The plant consi... ...f 4 trains i... first pass and three trains in the second p... . Eac... ...in in the ...cond pass has maximum capacity of 84... ...h. The pla... ...rte... ...oduction in November 2010.

The present study is ...ntinu...n of a pre...ious work which dealt with review of ...aste... ...y recove... in sea water reverse osmosis desalinati... plants [...

The objectiv... ...this study ... ...esent field results of the EPP-SWRO p... op...tion in orde... ...o measure and evaluate the performance improve...t due to using two different types of energy ...ry devices (...s).

2. ...view

Fa...ue [9] ...e explicitly described the performance and efficiency o... ERDs used in several sea water reverse osmosis ...RO) desalination plants in Saudi Arabia. They compared the e... ...of these ERD systems based on operating conditions ...one year. Also they assessed their effect on the high-pressure pump's total energy consumption and savings, along with an assessment of the energy loss incurred during the process stream of desalination plants. The mean efficiency of the assessed ERDs varied from 3.2% to 65%, enabling 1.5–27% savings on the high-pressure pump's total energy consumption. The mean power consumption of the pump ranged from 5.56 to 7.93 kWh/m^3. A significant amount of energy was wasted due to throttling, which consumed about 6.4–21.8% of the total energy supplied to the high-pressure pump.

A brief description of the energy recovery technology used during the desalination process in large plants was provided by Penate and Garcia-Rodriguez [10]. They described the modifications needed for the replacement of Pelton turbines with isobaric chamber devices. An exhaustive examination of the achievable levels of energy efficiency of these systems was also done.

An emerging technology based on the principle of pressure work exchange was put forth by Al-Hawaj [11]. The device employed a rotating member with multiple free-sliding double-sided ball pistons that functioned on pressure exchange between fluids that were pressurized at varying levels. He also discussed the technical aspects of the work exchanger apart from assessing the predicted efficiency based on qualitative comparisons with other ERDs.

Andrews [12] provided a historical overview of large scale ERDs that work on the principle of work exchange, beginning with the application of SWRO in 1975 to the present state of technology in desalination. As is evident from their work, technology based on work exchange has evolved tremendously since the time of its inception. They also described twelve years of the application of this technology in desalination plants.

Furthermore, an important and original calculation model was developed by Migliorini and Luzzo [13] to account for the different conditions of seawater based on carbonate equilibrium. The use of this classical equilibrium system for calculations enabled the

formulation of a complete mass and chemical balance of the system, along with the other characteristics of water. This model of calculation is not dependent on the characteristics of the membrane and so, can be used for a quick designing of the plant.

Farooque and Al-Reweli [14] have stated that Francis Turbines were popular in the early days of SWRO technology owing to their ease of use and simplicity. As briefly discussed in the previous section, Francis Turbine (FT) uses kinetic energy derived from brine coupled with the pump motor of the main feed to minimize the loss of energy during transfer from one fluid to the other. Due to their limited efficiency, which was below 75%, they lost their popularity and have been replaced by more efficient devices.

Baig [15] has investigated the theory of energy double dipping in hydraulic to mechanical assisted pumping devices, Pelton wheels and Francis Turbines. He stated that the maximum efficiency of Pelton wheels ranges between 80 and 85%. He emphasized the fact that the Pelton wheel and the FT share a common feature of transferring the energy recovered from brine back to the high pressure pump by coupling them to a common shaft. Computing total loss of energy, the energy lost by the high pressure pump and the reduction in the wheel's energy efficiency were taken into account. This is what was referred to as "double-dipping" in energy efficiency.

William and Andrews [16] described the DWEERTM energy recovery device to have two pressure vessels arranged in parallel. To avoid interrupting the flow of the reject, while one vessel is under operation, the other vessel is stationary, and has fresh feed. The pressure from the reject stream is transferred to the feed stream through a piston and the intermixing between the feed and reject is kept at a bare minimum. As the piston is designed in such a way that it has the least drag, the energy transfer between the two fluids is theoretically 100%. Therefore, the direct excha[illegible]f energy between the two fluids, i.e. the reject and the feed is [illegible] efficient when compared to ERDs that rely on the conversi[illegible] of energy by shaft of the turbines based on the centrifugal princ[illegible] In the DWEER system, by the time the piston in th[illegible]ing ves[illegible] completes its working stroke, the other vessel [illegible]omp[illegible]ely fille[illegible] with feed, and the functions are switched.

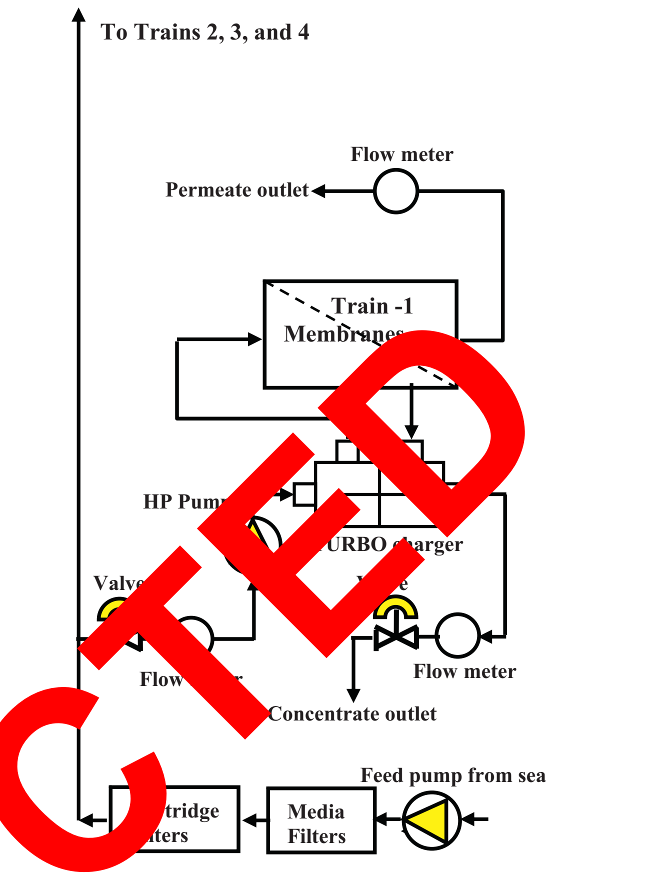
MacHarg [17] demonstrated how the PX [illegible]e [illegible] feed water directly. This is in contr[illegible] with [illegible]nergy recovery turbine, where the energy of [illegible] concentra[illegible] converted to mechanical energy by rotati[illegible]haft and th[illegible]covering energy. Because of the direct p[illegible]ssuriz[illegible] with PX device, there are no losses due to absen[illegible]f the transf[illegible]tion process in this case. This results in extr[illegible]ly high energy e[illegible]ency achieved by the PX devices. This w[illegible]onsid[illegible]ly reduce the power consumption of the SWRO p[illegible]em[illegible]ying these PX devices. The other researches [19–30] are [illegible]nphasi[illegible] on the necessity of ERDs for energy sa[illegible]SWRO[illegible]ts.

3. Gene[illegible]

The detaile[illegible]PP-SWRO plant flow diagram is shown in Appendix C while [illegible] simplified one is shown in Fig. 10. Generally, the plant main components are:

1. Intake
2. Multi media filters
3. Cartridge filters
4. Chemical system
5. Ro membranes units

The following subsections will discuss briefly the different parts of the plant [31].



[illegible] 10. EPP-SWRO plant process flow diagram with TURBO charger (train-1, 2, and

3.1. Intake

The intake is a beach well system (7 wells). The RO plant requires 277 m^3/h flow rate of raw seawater for one train producing 94 m^3/h. Based on the permeability of the soil, one beachwell can deliver a discharge of 150 m^3/h. Safety margins and standby requirements are considered in the total number of wells.

The beachwells are constructed according to the standard. The wells is equipped with submersible pumps. The well flushing and cleaning is done via high pressure pumps. The pump is a multistage submersible motor pumping set suitable for water application, particularly resistant to erosion and saline water, with the following characteristics:

- The nominal discharge at due point 277 m^3/h @ 40–60 m head.
- The suction from the well improves water quality, particularly regarding fine surrounding materials. The sand is acting as a natural filter.

3.2. Multi media filters

Each filter unit consists of 2 filters made from GRP -the first filter for sands and the other for activated carbon. The two filters are in series. The filter system is completely automatic with backwash facilities. The backwash water is collected in the brine outfall line.

3.3. Cartridge filters

The plant is provided with one cartridge filter which ensures that particles larger than 5 micron, carried over from the dual media

filters, will not enter the membranes. This filter is constructed from SS for total corrosion resistance.

3.4. RO unit

The first pass RO unit consists of 4 trains of three similar trains of 94 m^3/h capacity each and the fourth train of 124 m^3/h capacity. The output water salinity from the first pass is 238 ppm, measured as total dissolved solids (TDS). The second pass RO unit consists of three trains of 84 m^3/h permeate capacity each. The main function of the 2nd pass is to reduce the water TDS from 289 ppm at outlet from the first pass down to 8 ppm at outlet from the 2nd pass, as explained in Section 1.5. The first pass, trains 1, 2 and 3 are similar even in using the TURBO charger as energy recovery device. In the other hand train-4 is using Pelton wheel as energy recovery device.

3.5. Discharge

The outfall system includes one buried PVC pipe from the plant up to the seashore. The remaining part from the pipe (offshore pipes) is high-density PE laid down on the seabed with special covering. At the end of the outfall pipe a distributor header is fit to discharge the reject over a wide area. Although there are 7 wells for concentrate storage, it is not used yet due to design problems.

4. Measurements technique

Volume flow rates, gauge pressures, and salinity of water are the main parameters measured during the experimental tests. Remote Mount Magnetic Flowmeter System, Burdon tube pressure gauges and multi-range Conductivity/TDS meter are used for this purpose.

The accuracy is ±0.25% of full scale (FS) reading for magnetic flow meters, ±0.25% of FS for pressure gauges and ±1.5% of FS for TDS meter [31]. The readings are measured in different locations of the plant (TDS and flow rates and pressures before and after each component).

In order to obtain a measure of the reliability of the experimental data, an uncertainty analysis is performed for parameters of interest. Using uncertainties of the basic independent variables, the maximum uncertainties are less than 5.1% for Specific power consumption (SPC).

5. EPP-SWRO energy recovery devices

The EPP-SWRO plant employs a TURBO charger as ERDs for trains-1, 2, and 3 while for train-4, a Pelton wheel is used, as shown in Appendix C. The simplified schematic diagram for each type is shown in Figs. 9 and 10.

6. Data reduction

The Plant Performance data (pressures, Flow rates, and TDS) were collected from different points of measurements, during steady state normal operation of the plant. The calculation steps are given below.

6.1. Specific power consumption (SPC) calculations

The ideal hydraulic power to drive a pump depends on the mass flow rate, the liquid density and the differential height - either it is the static lift from one height to an other, or the friction head loss component of the system - can be calculated as follows [18]:

$$P_h = \frac{q\,\rho\,g\,h}{3.6\times 10^6} \qquad (1)$$

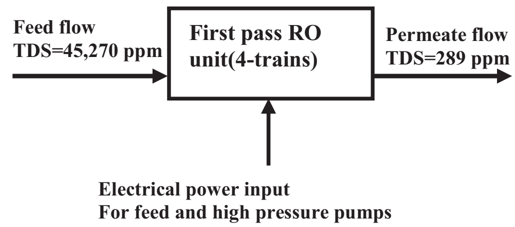


Fig. 11. Block diagram representing the first pass RO unit, showing the main inputs and outputs.

where P_h is the hydraulic power (kW), q is the flow capacity (m^3/h), ρ is the density of fluid (kg/m^3), g is the gravity (9.81 m/s^2), h is the differential head (m).

The shaft power is the power transferred from the motor to the shaft of the pump, which depends on the efficiency of the pump and can be calculated as:

$$Ps = \frac{Ph}{\eta} \qquad (2)$$

where η is the overall pump efficiency, which is taken equal to 0.6 during the present study.

Hence, specific power consumption can be expressed as:

$$SPC = \frac{P_{total}}{Q_{permeate}} \qquad (3)$$

where P_{total} is the total electric power consumed by feed and high pressure pumps, kW, and $Q_{Permeate}$ is the permeate flow rate at outlet from RO membranes unit, m^3/h.

6.2. Stage recovery calculations for RO passes (R%)

Recovery is the ratio of permeate to membrane feed flows, typically expressed as a percentage.

$$R\% = \frac{Q_{Permeate}}{Q_{feed}} \times 100 \qquad (4)$$

where $Q_{Permeate}$ is the permeate flow rate at outlet from RO membranes unit, m^3/h, and Q_{feed} is the feed flow rate at inlet to RO membranes unit, m^3/h.

7. Results and discussions

The performance of PPE-SWRO plant equipped with ERDs are studied and compared with the design. The results have been compared in terms of two important parameters SPC and $R\%$. As shown in Figs. 11 and 12, the main inputs and outputs are shown, for the first and second passes respectively. Now, in light of this, the results will be discussed as follows.

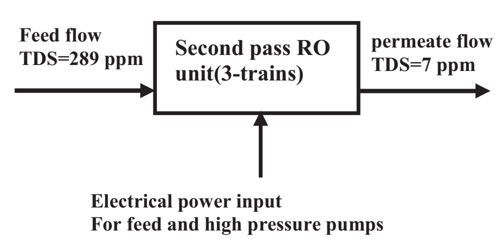


Fig. 12. Block diagram representing the second pass RO unit, showing the main inputs and outputs.

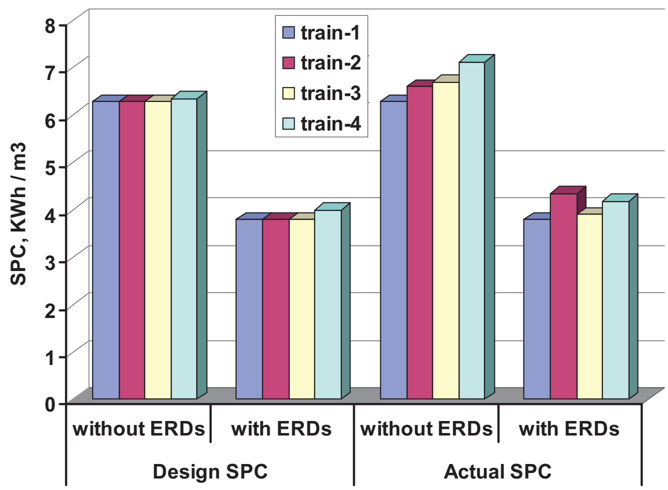


Fig. 13. Specific power consumption (SPC) for EPP-SWRO pass-1, compared with design ones.

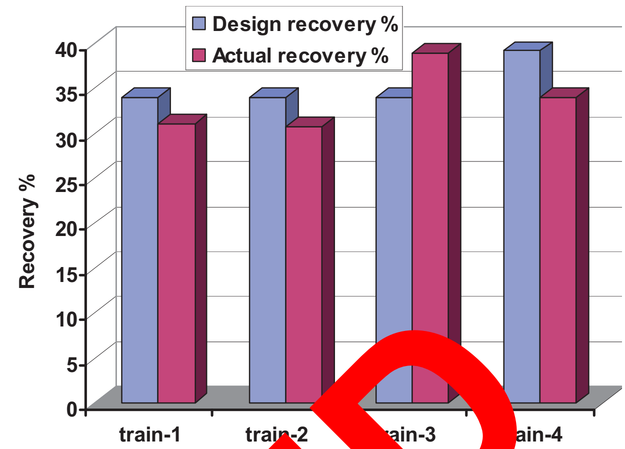


Fig. 15. Recovery % fo[illegible] pass compare[illegible]esign ones.

7.1. SPC results

Both of actual and design SPC results are shown in Figs. 13 and 14 for first and second passes respectively. From both figures the following points can be summarized:

a. For the first pass:
   1. without using ERDs, the SPC for all trains varies between 6:7 kWh/m^3, which agree with its corresponding desig[illegible]
   2. using ERDs, the SPC for all trains varies between [illegible]nd 4 kWh/m^3, which agree with its corresponding design o[illegible]
b. For the second pass: the SPC for all trains varies between 1.6 [illegible] 1.7 kWh/m^3, which agree with its correspondi[illegible]n ones.
c. Comparing between results in Figs. 13 and [illegible]t no [illegible]s condi[illegible]tion, it is observed that the SPC values f[illegible]econd [illegible] is much lower than values of the first pass. Thi[illegible]s du[illegible] [illegible]ity, which means higher recovery i[illegible]e seco[illegible]ge than in the first pass as shown in Figs. 15 a[illegible]
d. Comparing between ERDs use[illegible] t[illegible]4 (Pelton w[illegible]) and the other type used in trains-1, 2, and 3.

1. Generally, for train-4[illegible]e Pelton wheel is u[illegible]d to recover pressure energy from [illegible]entra[illegible]nd gives it back to the HP pump motor, throug[illegible]ts e[illegible] mech[illegible]al connection(external shaft) as sho[illegible]in Fig. 4. [illegible]is i[illegible]ns, causes more mechanical losses [illegible]e one used [illegible]ns-1, 2, and 3(TURBO charger shown [illegible]ig. 3[illegible]
2. From Fig. 13, for [illegible]-4, it clear that the Pelton wheel reduced t[illegible]al SPC from [illegible]7 down to 4.187 KWh/m^3. The resultant [illegible]ving is 41.25%. In t[illegible] other hand, The TURBO charger used [illegible]n trains-1, 2, and 3 reduced the actual SPC from 6.7 down to [illegible]9 KWh/m[illegible]e resultant saving is 41.79%. Although, the saving [illegible]n both t[illegible]s is close to each other, but the TURBO charger has t[illegible]ving due to lower mechanical loss, as indicated by many authors [5–8]. Also, it is recommended to retrofit to change [illegible]e existing ERDs and replace by the PX devices to get the highest e[illegible]gy saving.



Fig. 14. Specific power consumption (SPC) for pass-2 (train-1, 2, and 3), compared with design ones. Note that, no energy recovery device is used.

7.2. Recovery results

By the same way, both of actual and design $R\%$ results are shown in Figs. 15 and 16 for first and second passes respectively. From both figures the following points can be summarized:

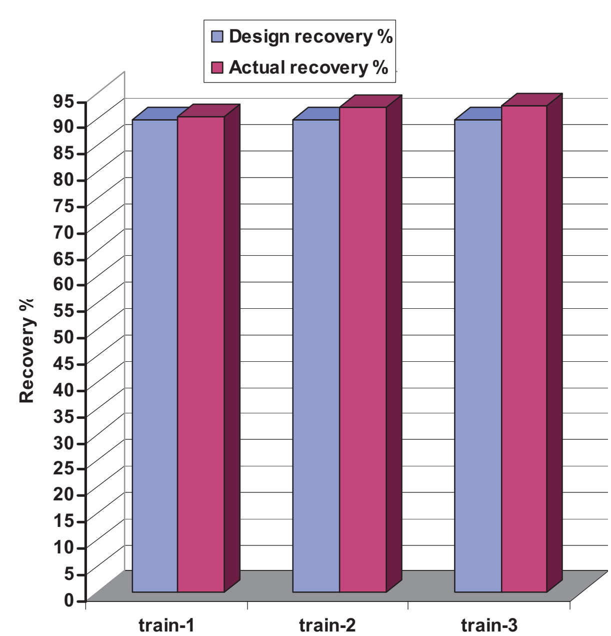


Fig. 16. Recovery % for the second pass compared with design ones.

1. For the first pass: The actual recovery varies between 31 and 34%, while the design values vary between 34 and 39%. This is very important indicator reflecting the RO membranes conditions, which needs good and continuous, follow up during plant operation and maintenance.
2. For the second pass: The actual recovery varies between 91 and 93%, which agrees with the design ones (90%).
3. Comparing between results in Figs. 15 and 16. It is observed that *R*% values for first pass is much lower than values of the second pass. This is normal and due to lower load of salinity.

8. Other environmental factors

Concern has also been raised about the potential environmental impact of concentrate discharges from desalination facilities. However, the majority of the known impacts are from thermal (distillation) facilities from which copper and other metals leached from the process are discharged. While RO Membrane desalination facilities, which use significantly less metal and operate at much lower temperatures, do not cause such impacts. Nevertheless, some desalination plants assure zero environmental impact by discharging the seawater concentrate far out to sea in open currents. At the PPE-SWRO desalination plant, the concentrate pipeline extends 470 meters from shore. The velocity of the discharge is up to 4 m/s through nozzles spaced at 5-m intervals to ensure total mixing of seawater concentrate within 50 m of each side of the pipeline. In future, the seven concentrate wells can be used after repair and the idea of food salt production from concentrate is under investigation.

Less concern has been raised about the environmental impacts of seawater intakes. Intake systems are designed to minimize entrainment of solids and marine life that must be removed by the pretreatment system before the water flows to the SWRO process. Open intakes are ideally placed in flowing currents to assure uniform, clean feed-water and intake velocities are minimized to prevent entrainment. Beach wells and ocean floor subsurface intakes are also widely employed.

9. Conclusions

The performance of EPP-SWRO desalination plant equipped with ERDs are studied and compared with the design. The results have been compared in terms of two important parameters SPC and *R*%. It is concluded that:

1. For the first pass:
   a. without using ERDs, the SPC for all trains varies between 6 and 7 kWh/m^3, which agreed with its corresponding design ones.
   b. Using ERDs, the SPC for all trains varies between 3 and 4 kWh/m^3, which agree with its corresponding design ones.
   c. The actual recovery varies between 31 and 34%, while the design values vary between 34 and 39%. This is very important indicator reflecting the RO membranes conditions, which needs good and continuous follow up during plant operation and maintenance.
2. For the second pass:
   a. The SPC for all trains varies between 1.6 and 1.7 kWh/m^3, which agreed with its corresponding design ones.
   b. The actual recovery varies between 91 and 93%, which agreed with the design ones (90%).
3. The Pelton wheel reduces the actual SPC from 7.127 down to 4.187 kWh/m^3. The resultant saving is 41.25%. In the other hand, The TURBO charger reduces the actual SPC from 6.7 down to 3.9 kWh/m^3. The resultant saving is 41.79%. The saving from both types is close to each other. Also, it is recommended to retrofit the plant to change the existing ERDs and replace by the PX devices to get the highest energy saving as recommended by many authors [28].
4. Retrofitting is recommended for the plant to use PX ERDs for higher saving of energy.
5. For environmental protection and to comply with Regulations, it is recommended to improve the concentrate discharge method, either by using the correct discharge wells or investigating the production of salt investment.

Appendix A. SWRO-ERDs with different configurations [5]

See Figs. A.1–A.8.

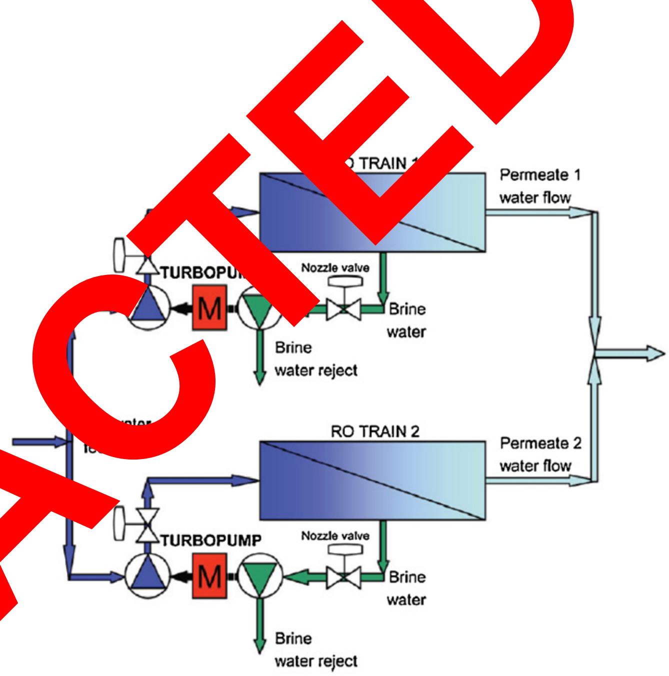


Fig. A.1. 10,000 m^3/d SWRO plant diagram using Pelton turbine energy recovery devices.

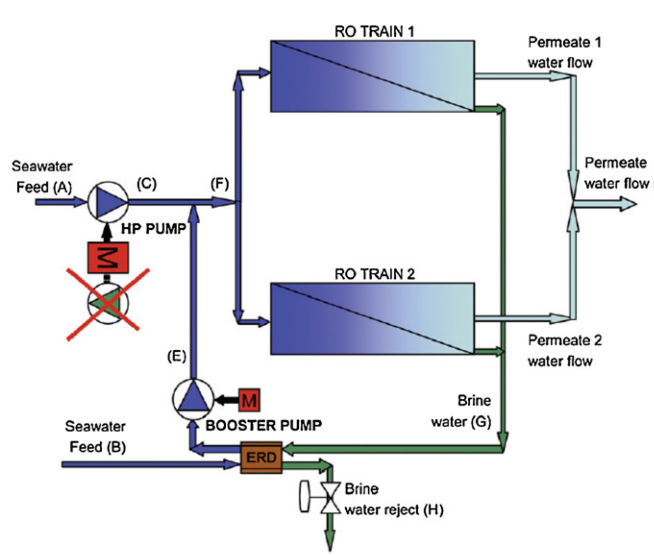


Fig. A.2. Retrofitt proposed in an existing SWRO plant – isobaric energy recovery device in a two 5000 m^3/d RO trains.

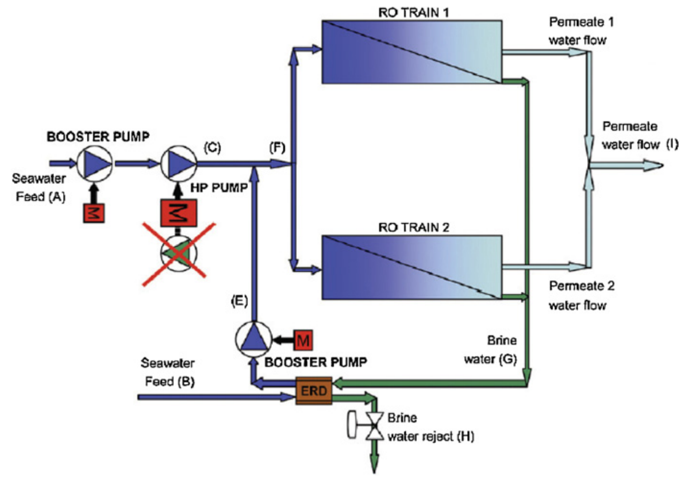


Fig. A.3. Retrofitt proposed in an existing SWRO plant – isobaric energy recovery device in a two 5000 m^3/d RO trains and a booster pump for the low-pressure feed water.

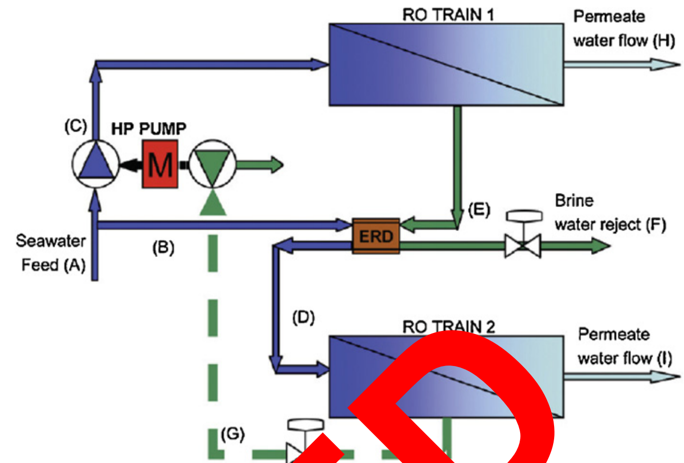


Fig. A.6. Isobaric energy reco device w a new R without booster pump and Pelton turbine.

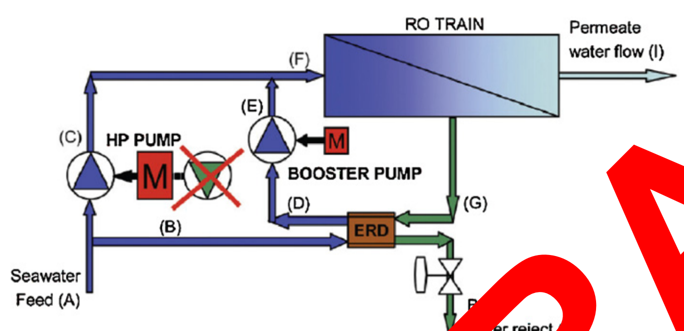


Fig. A.4. Installation of an isobaric energy recov device ier RO train.

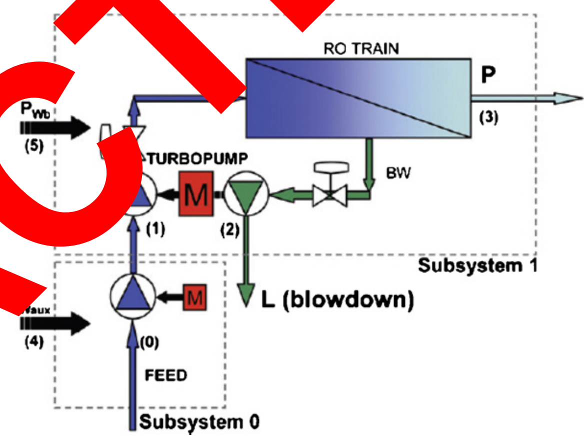


Fig. A.7. Flow chart of the whole productive process for the analysis in the case of standard configuration (existing desalination plants with energy recovery device based on Pelton turbine).

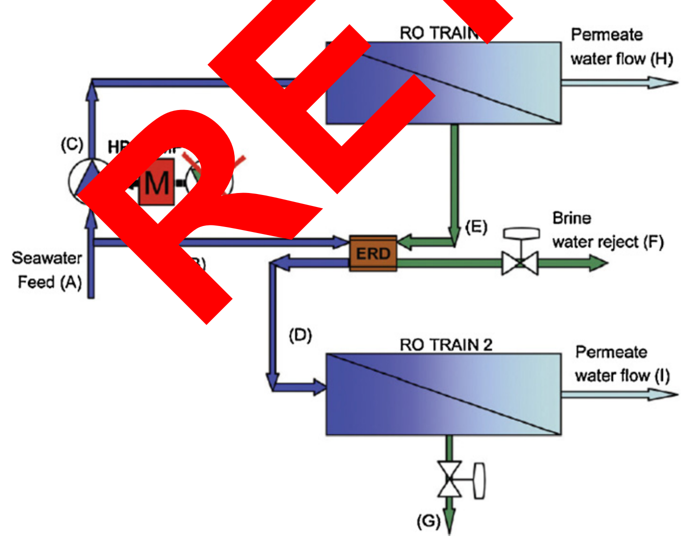


Fig. A.5. Isobaric energy recovery device with a new RO train without BOP.

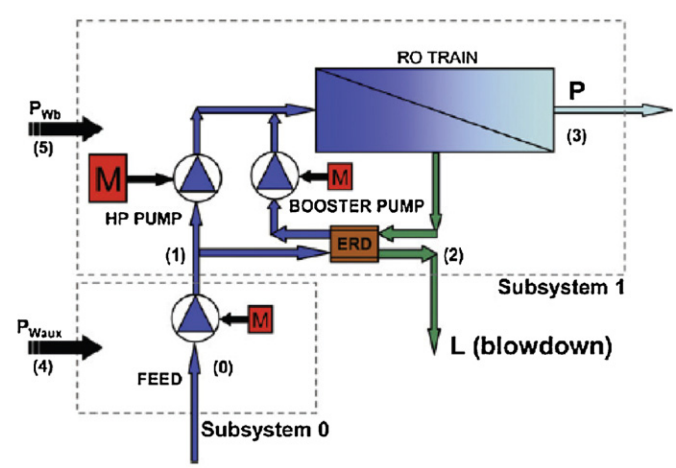


Fig. A.8. Flow chart of the whole productive process for the analysis in the case of retrofitting desalination plants (installation of energy recovery device based on isobaric chambers).

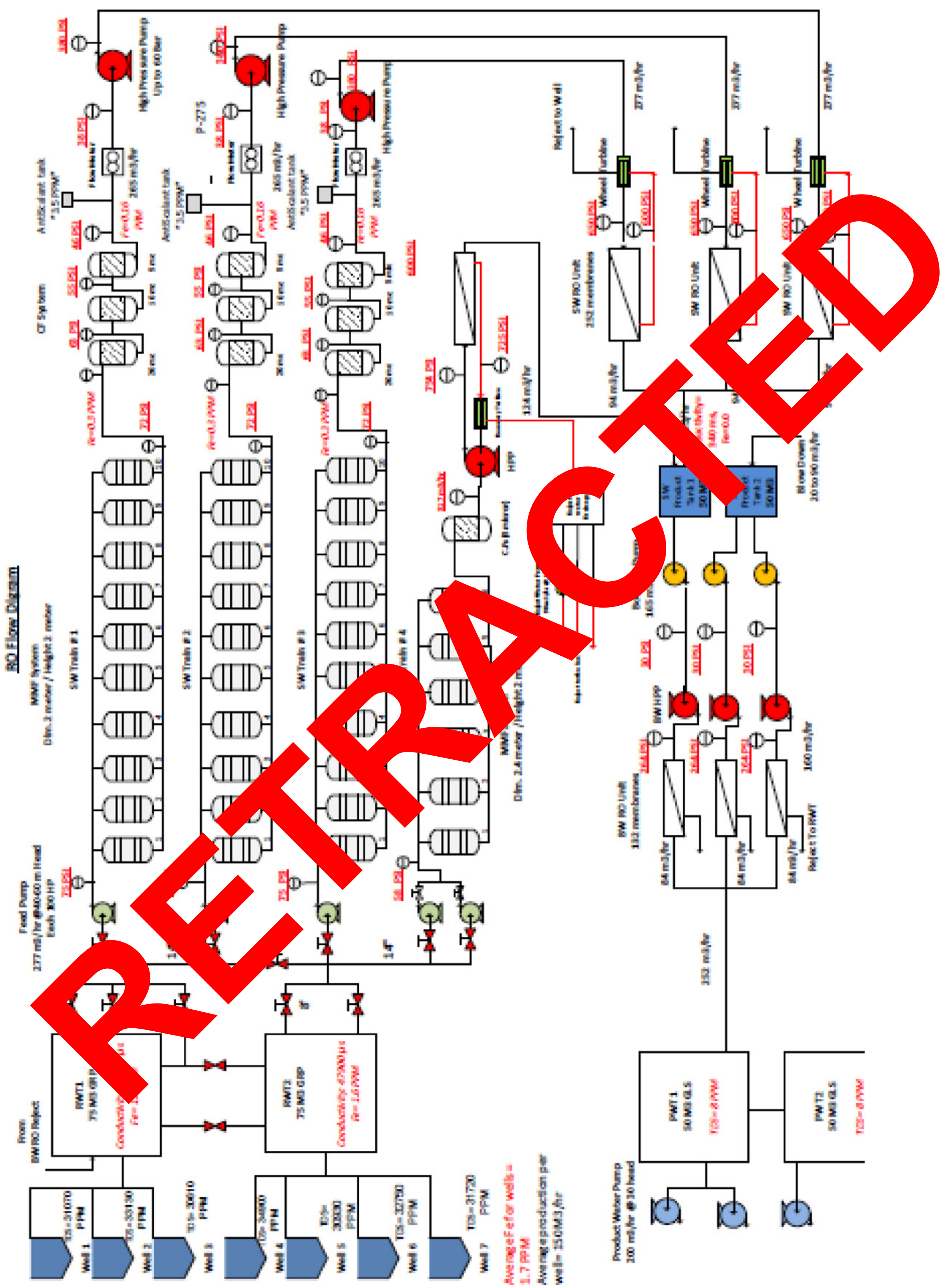
Appendix B. Different ERDs conclusive comparison [5]

See Table B.1.

Table B.1
Different ERDs conclusive comparison.

Type	Class	Maximum efficiency	Advantages	Disadvantages
Francis turbine	Hydraulic to mechanical assisted pumping	75–80%	• Low capital cost • Direct flange connection to be preferred over clutch	• Efficiency "Double Dip" • Narrow operating pressure and flow range • Lower efficiencies in regions wit[illegible] temperature [illegible]s • [illegible]ifficult to [illegible]in and [illegible]ntrol due to c[illegible] assembly • [illegible] suitable fo[illegible] flow ra[illegible]ue to p[illegible]efficiency
Pelton wheel	Hydraulic to mechanical assisted pumping	80–85%	• Low capital cost • Easy in operation • Optimization of Pelton [illegible] and nozzle design for [illegible]fficie[illegible] kinetic to mechani[illegible]ergy transformation • High efficie[illegible]tained over the f[illegible]era[illegible]nge	• Effi[illegible] "[illegible]le Dip" • Distri[illegible]ometry induces dissymme[illegible]y and secondary flow[illegible]t the inlet of the nozzle
ERT	Hydraulically driven pumping in series	90%	• Relatively low capit[illegible] • Spec[illegible]ally designed f[illegible] R[illegible]mall footprint a[illegible] [illegible]y to install, operate and [illegible]aintain • [illegible]sed duplex g[illegible]s of [illegible]less steel c[illegible]ion r[illegible]nt alloy [illegible] • No[illegible]oling or pneumatic requirements • [illegible]urbocharger and HPP are [illegible]ctly connected providing a degree of flexibility	• Limitation of only being able to recover 50–80% energy • Efficiency decline in accordance with the efficiencies of impeller, nozzle and turbine • Efficiency decline as the flow rate or pressure of the reject stream strays from optimal
Recuperator	Hydraulically driven pumping in parallel	92-[illegible]	• Directly transfer of brine hydraulic energy to feed hydraulic energy without going through shaft work • Seawater of the same flow and pressure as the saline reject with no mixing • HPP required is about 60% smaller than that of the traditional technology	• High capital cost • To compensate for the pressure drop across the membranes (0.5–1.5 bar) and in the Recuperator system (0.2–0.6 bar) a booster pump that can take high suction pressure is needed • Mixing, lubrication, overflush, high pressure differential, low pressure differential
DWEER	Hyd[illegible]ally d[illegible] pumpi[illegible]n [illegible]llel	[illegible]%	• Brine and feed are separated by a piston to ensure minimum mixing • For a piston designed for minimum drag the transfer of energy is essentially 100%	• High capital cost • Booster pump is needed • Mixing, lubrication, overflush, high pressure differential, low pressure differential
PX	[illegible]ydraulic[illegible] [illegible]riven pump[illegible] in [illegible]	98%	• Core built of ceramic selected to be the ideal material for its toughness, corrosion resistance and dimensional stability withstanding the harshest saline environments. Unlike turbines no transformational losses occur in a PX device • Stable efficiency over wide range of recoveries • Lack of traditional seals and bearings	• High capital cost • Booster pump is needed • Complexity of design, operation and maintenance • Mixing, lubrication, overflush, high pressure differential, low pressure differential

Appendix C. General layout of EPP-SWRO desalination plant [31]



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